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NAVORD REPORT 6876

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THE ATTENUATION OF SHOCK IN LUCITE (U)

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U. S. NAVAL ORDNANCE LABORATORY

WHITE OAK, MARYLAND

THE ATTENUATION OF SHOCK IN LUCITE

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ABSTRACT: The attenuation of the velocity of a shock wave was measured in Lucite under conditions similar to those of the shock sensitivity test. Two systems, one based upon the reaction of pressure probes to the pressure pulse of the shock wave and the other a smear camera, were used to record the events. The reliability of the pressure probe in recording the events was comparable to the smear camera record of the shock for the first three inches of Lucite after which the response lagged behind the camera record. With the aid of the smear camera, additional data were calculated for Lucite in the low pressure region (4-5 kbar) by measuring the shock velocity in Lucite and water. These data were used to extend the equation of state for Lucite to the region applicable to this investigation.

The shock pressure in Lucite was calculated as a function of the Lucite length from the velocity obtained experimentally and the equation of state for Lucite. This was compared to the length of the gap in the shock sensitivity tests to obtain an approximate value of the pressure required for the initiation to detonation of various explosives.

An investigation of the effect of varying donor length on the shock transmitted into Lucite has been initiated.

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Gap tests for explosives, in which sensitivity of an explosive is measured by interposing a gap of some inert material between a high explosive donor and the explosive under test, have been used for a number of years. The mechanism of initiation by shock and the meaning of gap sensitivity in relation to other sensitivity tests and to handling experience has now become of considerable interest. In the case of composite propellants, gap tests seem to reflect handling hazards of finished grains more accurately than the impact test. For this reason calibration of the gap test is of importance to knowledge of propellant sensitivity.

This research covers part of a program to calibrate the card gap test in terms of basic parameters; in this case, in terms of the minimum pressure required to initiate detonation under the conditions of the experiment. This represents an important advance in deducing the energy input and energy flux relations which are believed to be the basic information required to interpret gap sensitivities.

This research was supported by Task NOL-323, Polaris Sensitivity.

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Captain, USN
Commander

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ALBERT LIGHTBODY
By direction

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THE ATTENUATION OF SHOCK IN LUCITE

I. INTRODUCTION

The present investigation was made to interpret the shock sensitivity test results in terms of shock pressure rather than the gap thickness required to initiate the explosive. The present work was carried out on Lucite rods, since it was determined cellulose acetate (used in forming the gap) and Lucite were similar shock attenuators. The investigation consisted of extending the equation of state data of Lucite to the lower pressures in the gap and of using the data obtained to relate pressure and gap thickness for the conditions under which the gap tests are made.

The equation of state data were obtained by initiating a shock with two cylindrical tetryl pellets (each 2 inches dia. x 1 inch thick) and measuring the shock velocity as a function of distance in Lucite rods and in water (the equation of state of which is known) as it progresses from the Lucite to the water. Using the customary approximation at the Lucite-water interface, the pressure and particle velocity in Lucite before the interface may be obtained.

II. EXPERIMENTAL METHODS

The attenuation of the shock velocity in Lucite was determined by two different experimental techniques. One was based upon recording the passage of a pressure pulse by an electronic system, and the other used high speed photography to follow the shock front. This latter technique was used to obtain additional data to determine a more accurate curve for the equation of state of Lucite.

A. Electronic System Used to Measure Shock Velocity

Figure I is a schematic drawing of the experimental assembly used to measure the attenuation of a shock wave in a Lucite rod. A donor, consisting of a tetryl pellet or a series of tetryl pellets, was initiated by a Seismo* detonator. The detonation wave developed in the tetryl becomes a shock wave in the Lucite rod. The progress of the shock wave was followed by a series of pressure probes carefully placed in the assembly. Basically the probes act as switches which in one case were shorted by an ionization front (i.e. as an ionization probe used to trigger the measurements) and otherwise by a pressure pulse (i.e. acting as a pressure probe). The pressure pulse impinged

* Detonators were obtained from Olin Mathieson.

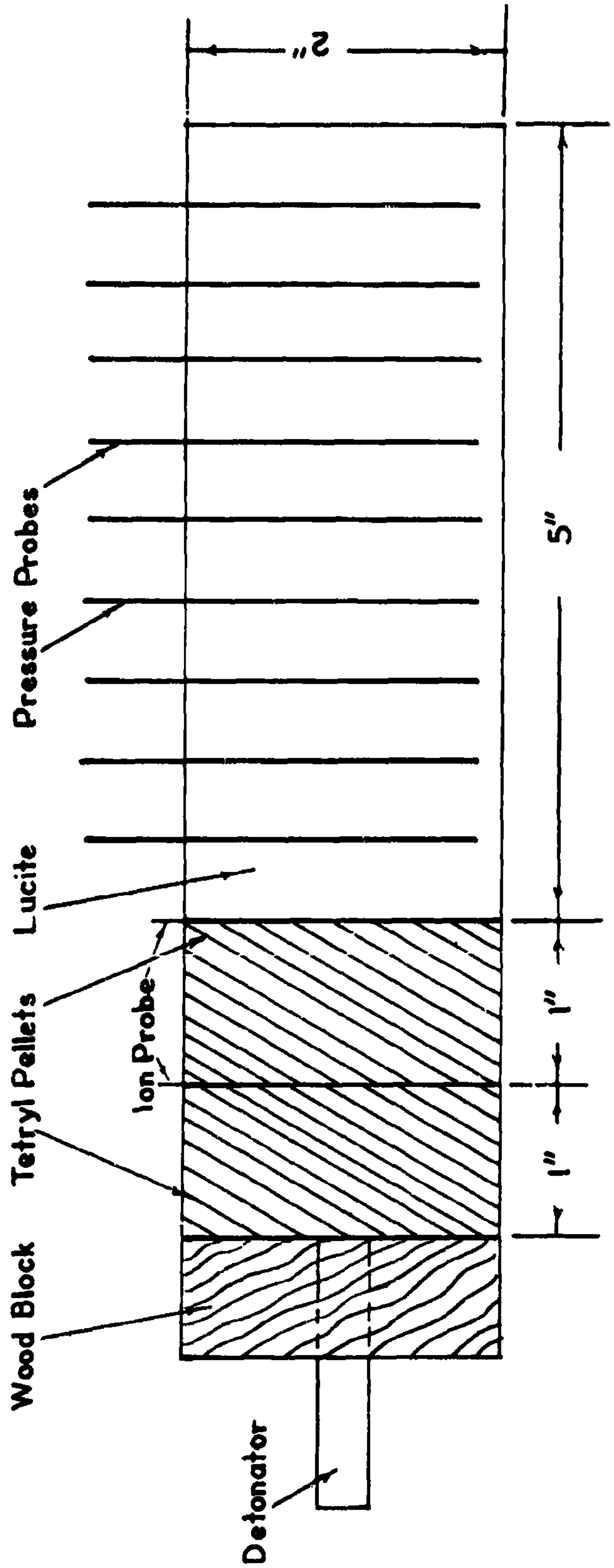

FIGURE 1.- ASSEMBLY FOR THE MEASUREMENT OF SHOCK ATTENUATION IN LUCITE

on a copper tube 0.033 inches away from a copper wire. When these two made contact, a circuit was closed and an impulse was transmitted to an oscilloscope (Tektronic No. 535). A Polaroid camera was used to make permanent records of the oscillograph tracings. Figure II is a schematic drawing of the pressure probe.

A series of holes 0.053 inches in diameter were carefully made at specified intervals in a Lucite rod. The pressure probes were inserted and the necessary leads were soldered to the probes. The tetryl pellets were securely taped to the Lucite rod. An ionization probe was inserted between the last two tetryl pellets, and at the tetryl-Lucite interface. The entire ensemble was placed in the bombproof chamber where the leads were connected to the oscilloscope and the detonator put in place. Meanwhile a series of calibrated time marks was obtained on the oscilloscope by using a Tektronic No. 181 Time-Mark Generator. The time scale was recorded on the film just prior to the experiment.

The oscilloscope was triggered by the ionization probe placed between the last two tetryl pellets. By beginning the oscilloscope sweep prior to the arrival of the detonation at the Lucite-tetryl interface, a much more definitive and precise measurement was obtained of the time of arrival of the shock in the Lucite. (In the instance when one pellet was used, the ionization probe placed at the tetryl-Lucite interface was used as a trigger.) The arrival of the reactive shock at the tetryl-Lucite interface was recorded by the second ionization probe. The further progress of the shock wave down the Lucite rod was followed by the pressure probes. A more comprehensive discussion of the pressure probe and the electronic system used is given elsewhere (1,4).

The system of most interest was the one containing a donor made up of two tetryl pellets, since these are the conditions in the shock sensitivity test. Cellulose acetate cards, 0.01 inches thick by 2 inches in diameter, are used to build gaps less than one-half inch thick. For larger gaps, Lucite discs, one-half inch and 1 inch thick are used with the cellulose acetate cards to build the required gap. A number of charges was prepared in the exact manner used for the shock sensitivity tests and ionization probes were placed at designated positions in the Lucite-cellulose acetate gap (Figure III). The gap was prepared by stacking the cards and discs in units one to two inches high. Each unit was compressed to form a compact pile and a hole was drilled in it for a pressure probe. The attenuation of the shock velocity was measured at 0.5, 1.0 and 1.5 inches and compares with the shock velocity measured in the Lucite rod.

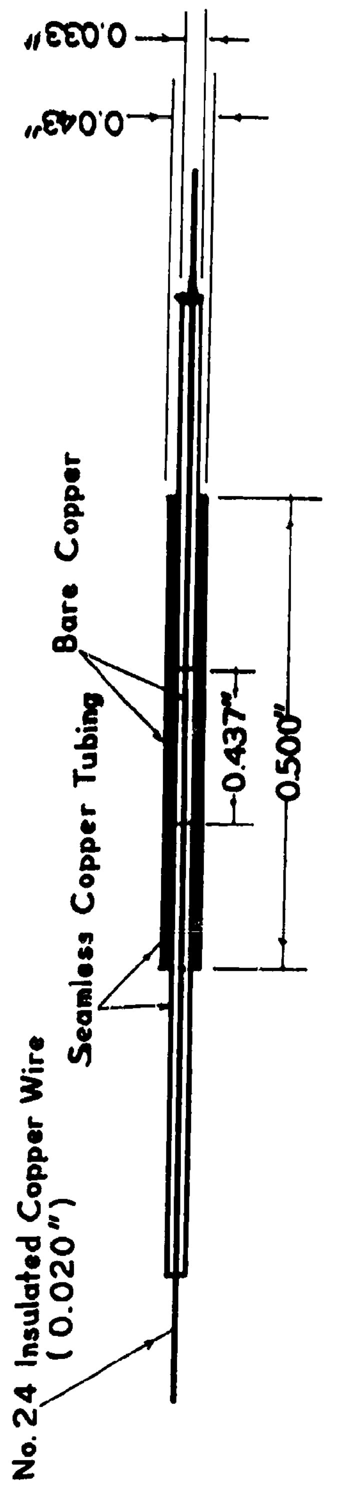

FIGURE II.- SCHEMATIC- PRESSURE PROBE

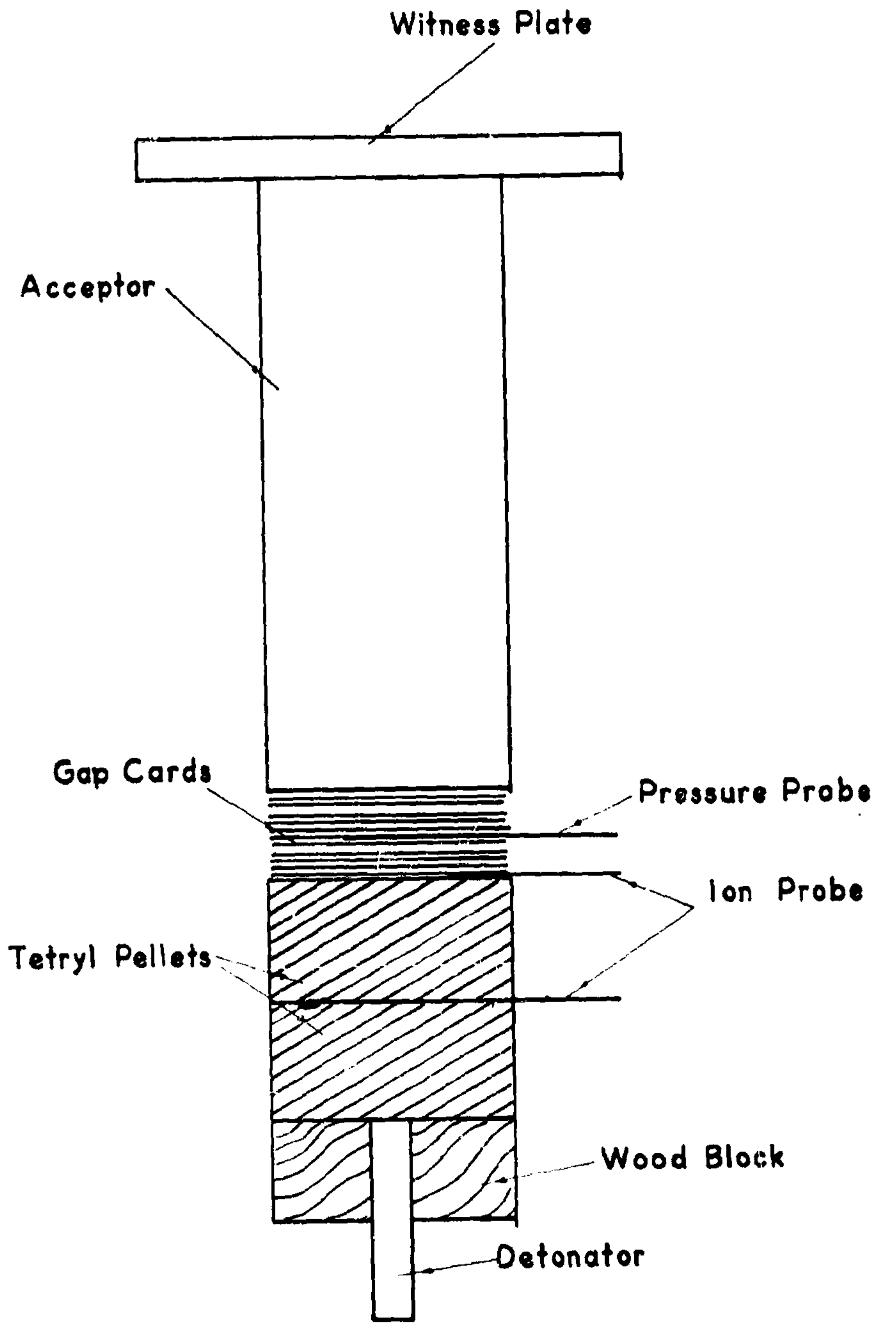

FIGURE III.- ASSEMBLY- SHOCK ATTENUATION IN THE GAP

B. High Speed Photography

The objects of this experiment were three-fold:

1) to measure the attenuation of the shock wave in Lucite by an alternate method;

2) to determine the reliability of the measurements made by the pressure probes; and

3) to obtain data which will define more precisely the equation of state of Lucite for the lower shock pressures.

Figure IV is a schematic drawing which shows the arrangement of the various components. The Lucite rod was machined from a bar 2 inches x 2 1/4 inches in cross section to a rod approximately 2 1/16 inches in diameter with two parallel flat surfaces 2 inches apart and 5/8 inches wide. These parallel flats eliminated distortion of the light by the curved surfaces as the light passed through the Lucite rod. Pressure probes were inserted at designated points in the usual manner. The rod was supported vertically with its end submerged approximately 1/4 inch below the surface of the water contained in a small trough. A Lucite blast shield of known thickness was placed on top of the Lucite rod to prevent the products, resulting from the detonation of the tetryl pellets, from obscuring the view of the camera. Above this shield were placed the two tetryl pellets and the detonator. The ionization probe used to trigger the camera and the oscilloscopes was placed at the tetryl-Lucite interface.

To record the reaction two oscilloscopes, a Tektronic No. 535 and a raster oscilloscope were used in conjunction with the smear camera. A spark was arranged to go off at the end of the reaction to provide a common point, on both the oscilloscope and the camera records, from which the time intervals could be measured and compared. The illumination for the camera was obtained from an exploding wire set behind the Lucite rod. Four experiments were performed, two using four-inch long Lucite rods and two using three-inch long Lucite rods.

III. RESULTS

Figure V is a typical record of the attenuation of a shock wave measured by the pressure probes in a Lucite rod using the sweep oscilloscope. The time scale is 1 μsec per division, and can be read to ± 0.5 μsec. The alternate positive and negative response of the pressure probes, as they were activated, made it possible to determine the position of any malfunctioning probe. Table I contains the results of the experiments performed

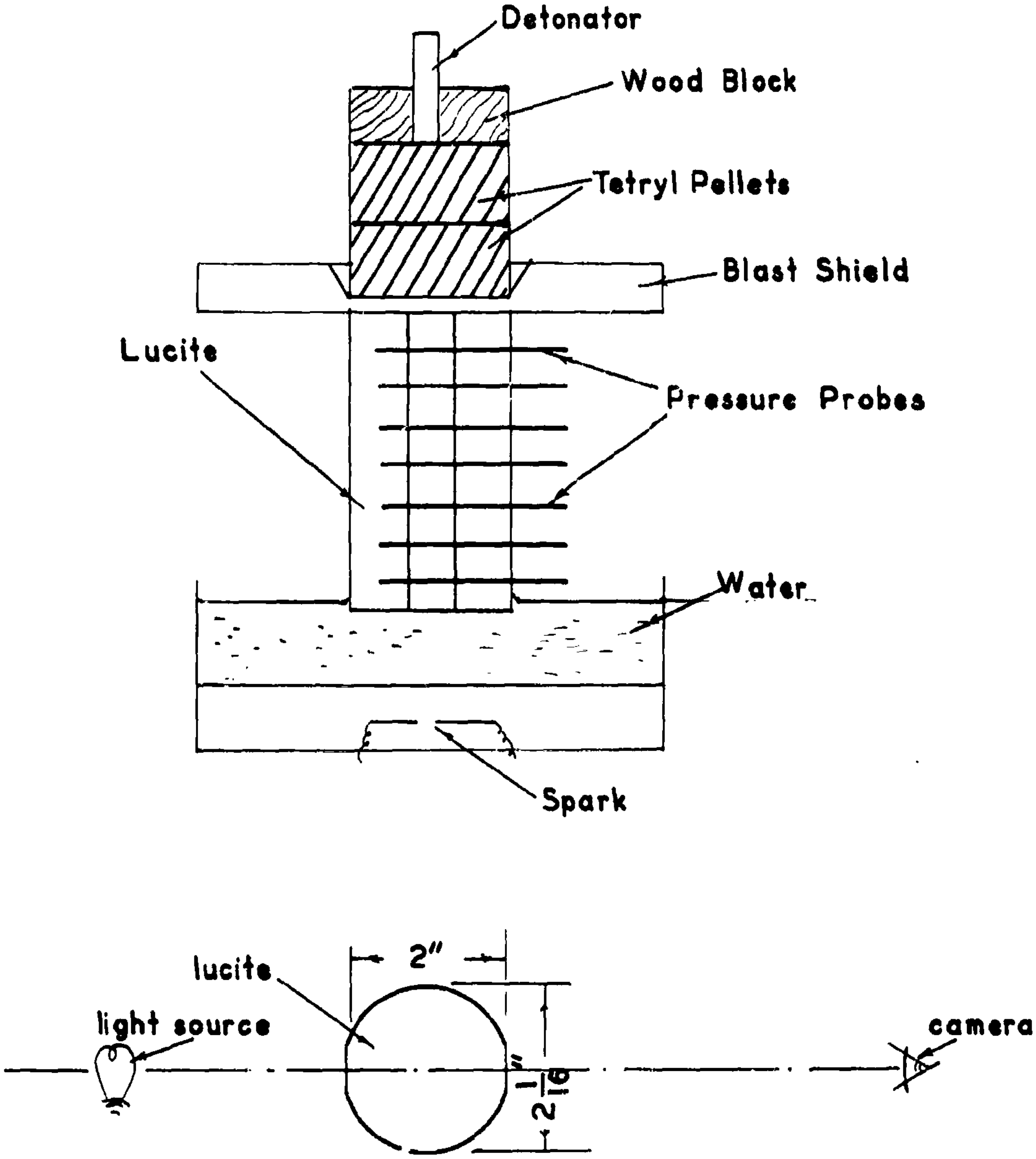

FIGURE IV.— SHOCK ATTENUATION IN LUCITE AND WATER

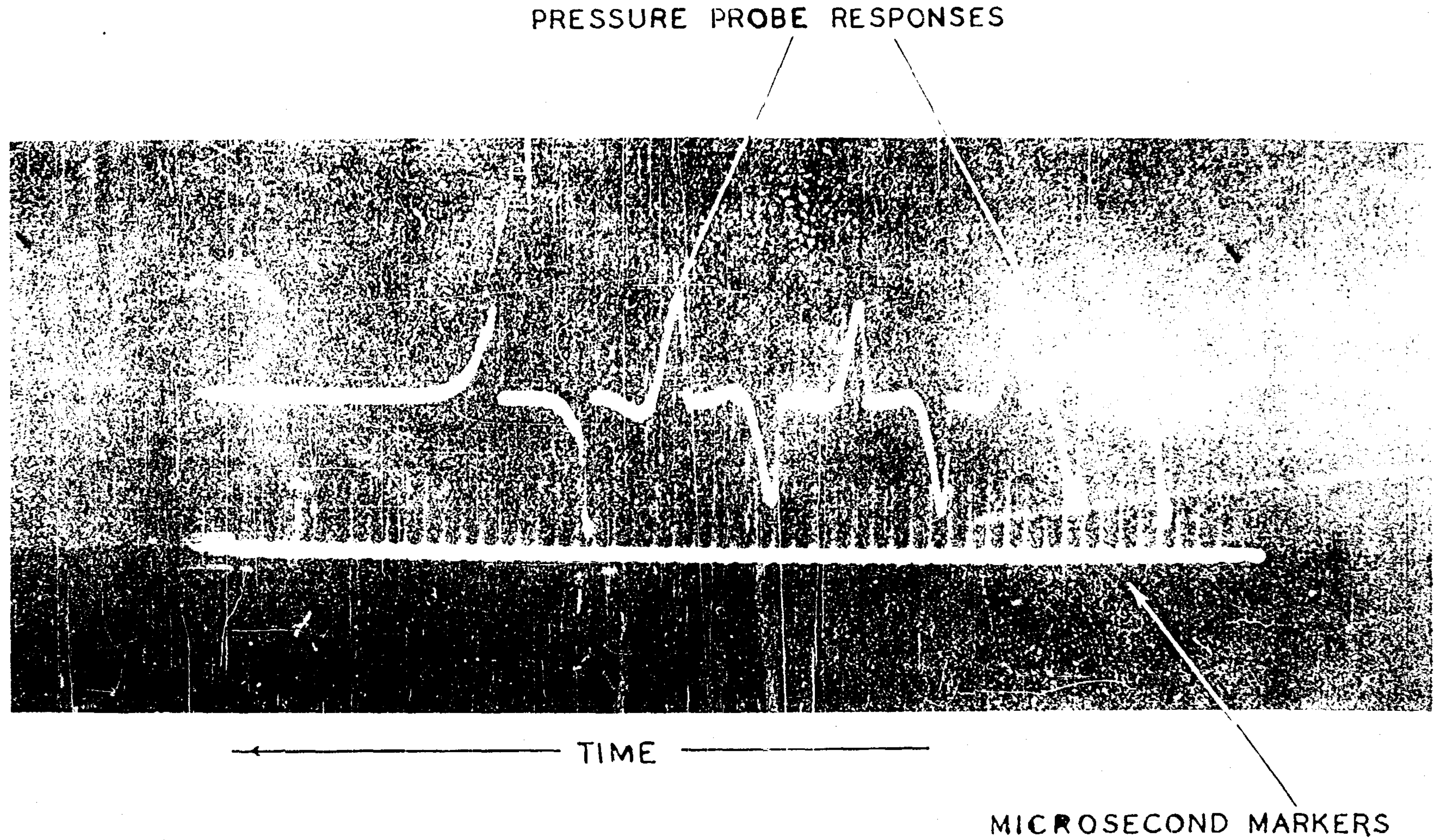

FIGURE V - RECORD OF THE PRESSURE PROBE RESPONSE

TABLE I

ATTENUATION OF SHOCK IN A LUCITE ROD (Pressure Probe)

(Two Tetryl Pellets)

Distance of Probe		Time (Microseconds)				Mean
in.	mm.	Expt.#1	Expt.#2	Expt.#3	Expt.#4	microsec
0.5	12.7	-	-	2.5	3.0	2.8
1.0	25.4	5.2	6.0	5.5	6.2	5.7
1.5	38.1	8.6	9.6	9.2	9.5	9.2
2.0	50.8	12.0	13.5	12.8	-	12.8
2.5	63.5	16.1	17.8	17.0	17.4	17.1
3.0	76.2	20.5	-	21.1	21.4	21.0
3.5	88.9	25.1	26.5	25.2	26.0	25.7
4.0	101.6	29.7	31.0	29.6	31.1	30.4
4.5	114.3	33.7	37.0	33.7	35.5	35.0
5.0	127.0	-	-	-	-	-
ATTENTUATION OF SHOCK IN GAP UNITS						
0.53	13.4	2.7	-	75 - 0.01 in. acetate cards		
1.00	25.4	6.1	6.0	1/2 in. Lucite disc and 75 - 0.01 in. cards		
1.50	38.2	9.5	9.5	1 in. Lucite disc and 75 - 0.01 in. cards		

using two tetryl pellets with the Lucite rods and the gap card units. Table II contains the results of the experiments made with one, three and four tetryl pellets, respectively, and Lucite rods.

Of the four experiments (Expt. #5,6,7 and 8) made using the electronic system and the smear camera, only two could be used for comparison between the two systems. In experiment #7 the fiducial point was not obtained while in experiment #8 the electronic system did not respond satisfactorily. Figure VI shows the records obtained from the smear camera and the raster oscilloscope.

The time scale on the raster oscilloscope was 0.1 microseconds per division and could be read to ± 0.02 microseconds. The time scale for the photographic records was 1.263 mm per microsecond and could be read with a microcomparator to better than ± 0.02 microsecond. The magnification factor for the camera was determined for each experiment by measuring the distance between the probes on the film and relating this to the actual distance between probes. The same magnification factor was used to interpret distance for the shock wave in the water.

Tables III and IV contain the results obtained by the smear camera. The results listed in Table III were obtained by choosing an arbitrary point on the film strip as zero and measuring both time and distance from this point. The data in Table IV were measured from the fiducial point (spark).

TABLE II

ATTENUATION OF SHOCK IN LUCITE ROD (Varying Load)

Distance		Time (mm/microseconds)		
inches	mm.	1-Tetryl	3-Tetryl	4-Tetryl
0.5	12.7	3.3	2.6	2.2
1.0	25.4	6.7	5.3	4.6
1.5	38.1	10.4	8.4	7.5
2.0	50.8	14.6	12.3	11.4
2.5	63.5	19.0	-	15.6
3.0	76.2	23.6	20.6	19.8
3.5	88.9	27.5	25.4	24.7
4.0	101.6	33.6	27.4	29.4
4.5	114.3	44.6	31.7	34.3
5.0	127.0	-	-	-

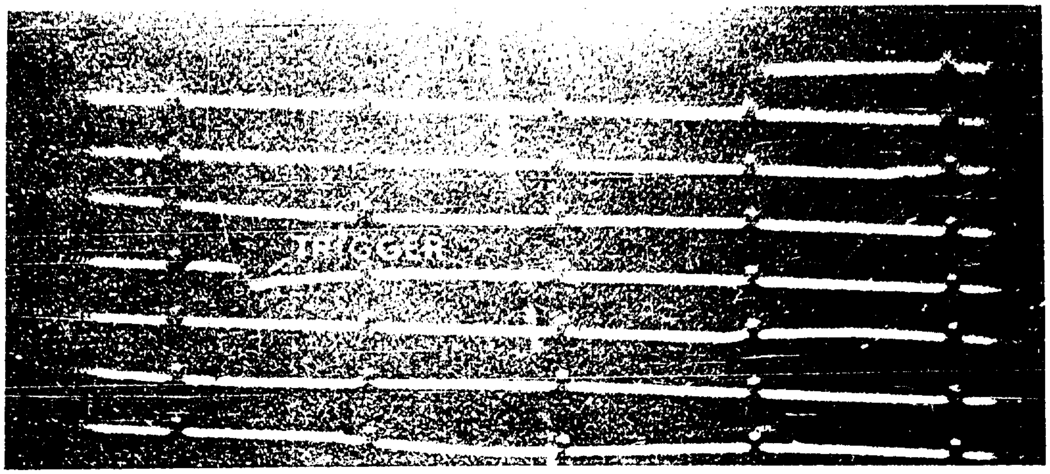

FIGURE VI-A- SECTION OF THE RASTER RECORD

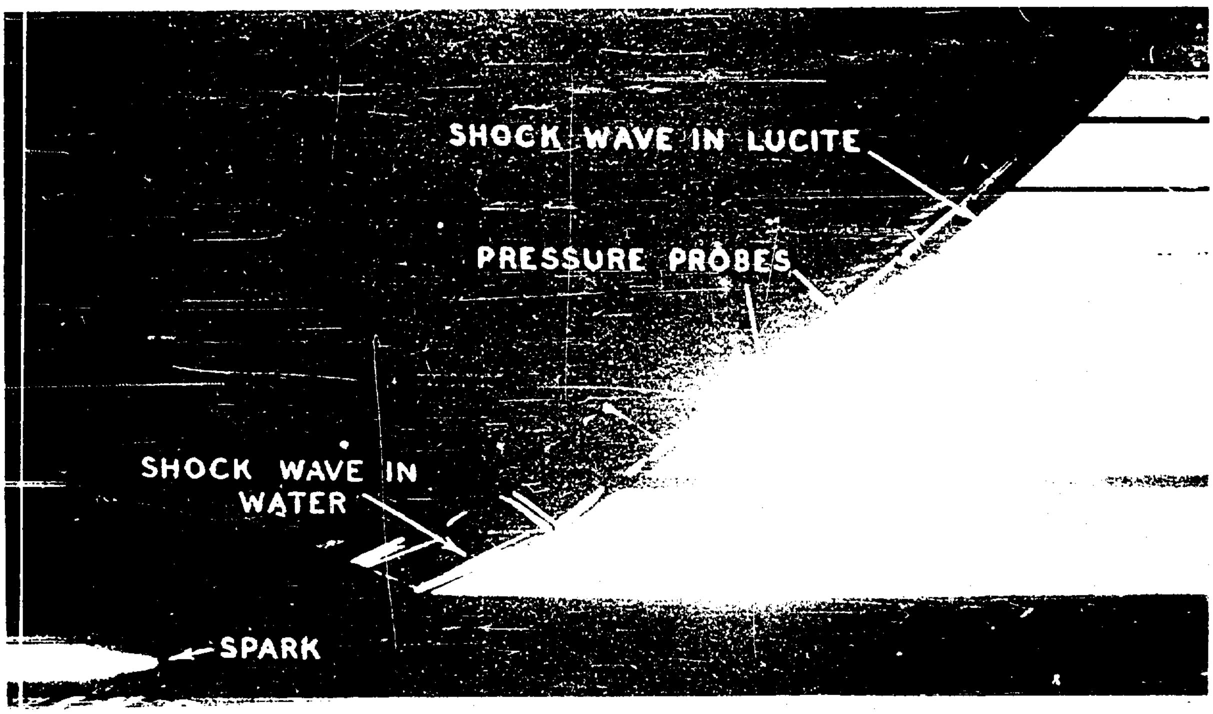

FIGURE VI-B- CAMERA RECORD OF SHOCK WAVE IN LUCITE AND WATER

TABLE III

ATTENUATION OF SHOCK IN LUCITE AND WATER*

Shock in	Expt.#5,4" Lucite Rod Time(mm)	Expt.#5,4" Lucite Rod Dist.(mm)
Lucite	0	0
	0.536	0.804
	1.039	1.316
	1.611	1.995
	2.446	2.901
	3.509	4.005
	4.560	5.033
	5.556	5.983
	7.126	7.593
	8.793	9.144
	10.289	10.454
	11.736	11.652
	13.289	12.956
	15.015	14.334
	16.746	15.695
	18.546	17.097
	20.077	18.244
	22.157	19.813
	23.427	20.780
	25.258	22.141
	26.517	22.991
	28.962	24.914
	30.142	25.767
Lucite in H_2O	32.605	27.410
	33.970	28.405
	35.156	29.268
Interface		29.427
Water	35.706	29.659
	36.438	29.994
	37.406	30.413
	38.731	30.999
	40.756	31.893
	43.471	33.098

Shock in	Expt.#6,4" Lucite Rod Time(mm)	Expt.#6,4" Lucite Rod Dist.(mm)
Lucite	0	0
	0.801	0.694
	2.282	2.240
	3.615	3.495
	4.820	4.467
	6.299	5.888
	7.592	6.979
	9.037	8.044
	11.100	9.660
	12.981	11.223
	14.145	11.951
	16.223	13.632
	17.965	14.915
	19.317	15.762
	21.392	17.376
	23.182	18.687
	24.955	19.908
	26.700	21.134
	28.659	22.534
Lucite in H_2O		
	30.284	23.439
	31.198	24.082
	32.114	24.669
	32.897	25.197
Interface		25.807
Water	33.882	26.024
	34.972	26.489
	36.483	27.105
	38.781	28.114
	40.911	29.025
	42.902	29.867
	44.784	30.662
	46.406	31.315

TABLE III, Cont'd.

Shock in	Expt.#7, 3" Lucite Rod Time (mm)	Expt.#7, 3" Lucite Rod Dist. (mm)	Shock in	Expt.#8, 3" Lucite Rod Time (mm)	Expt.#8, 3" Lucite Rod Dist. (mm)
Lucite			Lucite		
	0.996	1.522		0.574	1.055
	2.098	3.184		1.133	1.852
	3.320	4.913		1.788	2.876
	4.966	7.146		2.636	4.124
	6.183	8.812		4.196	6.357
	7.883	10.965		5.398	8.030
	9.438	12.847		6.628	9.686
	10.521	14.116		8.409	11.982
	11.979	15.802		9.910	13.802
	13.935	17.972		11.476	15.643
	15.544	19.680		13.008	17.354
	17.274	21.546		14.426	19.000
	18.583	22.936		16.112	20.841
	19.680	24.093		18.111	22.975
	21.184	25.685		19.877	24.856
	21.961	26.463		20.463	25.458
Lucite in H_2O	22.720	27.276	Lucite in H_2O	21.649	26.716
	23.335	27.884		23.363	28.330
	24.751	29.367		24.195	29.242
Interface		29.540	Interface		29.366
Water	25.351	29.919	Water	24.761	29.785
	26.730	30.802		25.533	30.277
	28.069	31.670		27.139	31.382
	29.871	32.842		28.718	32.428
	31.532	33.913		30.197	33.399
	33.453	35.130		31.505	34.253
				32.278	34.765

* The data given here are the readings made directly from the films. The magnification and time factors are given in Table VI.

TABLE IV

RESULTS OF EXPERIMENTS #5 AND #6 USING THE CAMERA RASTER AND SWEEP OSCILLOSCOPE

Probe No.	Distance from Donor (mm)	Distance from Spark			C - S	C - R
		Sweep Scope S(μsec)	Raster Scope R(μsec)	Camera C(μsec)	Δ(μsec)	Δ(μsec)
Expt. #5						
1	4.2	47.43	47.72	48.0	+ 0.6	+ 0.3
2	12.0	45.73	46.08	46.31	0.6	0.2
3	22.1	43.37	43.65	43.90	0.5	0.3
4	34.6	40.27	40.36	40.48	0.2	0.1
5	47.4	36.59	36.59	36.89	0.3	0.3
6	60.1	31.97	32.14	32.66	0.7	0.5
7	72.7	28.27	28.24	28.80	0.5	0.6
8	85.3	23.29	23.38	24.42	1.1	1.0
Spark		0	0	0		
Expt. #6						
1	4.2	46.52	47.01	-	-	-
2	12.0	45.12	45.56	44.97	- 0.1	- 0.6
3	22.1	42.32	42.77	42.77	+ 0.4	+ 0.0
4	34.6	39.25	39.61	39.61	0.4	0.0
5	47.4	35.34	35.68	35.75	0.4	0.1
6	60.1	-	-	31.74	-	-
7	72.7	26.70	27.01	27.71	0.9	0.6
8	85.3	22.50	22.74	23.56	1.1	0.8
Spark		0	0	0		

IV. DISCUSSION

In the hydrodynamic theory of shock waves, the conservation of momentum requires that

$$P = \rho_0 uU \qquad (1)$$

where the initial pressure (P_0) and particle velocity (u_0) are assumed to be zero and where

P = shock pressure

ρ_0 = initial density of the material

u = particle velocity

U = shock velocity.

In order to obtain the pressure at any point in a shocked homogeneous medium, it is necessary to measure the shock velocity and the particle velocity. However, if a set of data corresponding to equation (1) is known, i.e. the equation of state of the medium is known, a measurement of U vs the attenuation path length (X) for the test geometry can be combined with the known data to give a P - X curve. Since it was desired to use the pressure probes to obtain the U - X data, their adequacy for such measurements was investigated.

A. Pressure Probe Reliability

The construction of the pressure probe (Fig. II) causes a time lag between the arrival of the shock and its recording. The distance between the bare copper wire and the outer copper tube is approximately 0.013 inches. To record the shock, the copper must travel this distance to make contact with the inner core. Moreover, the time lag should increase as the shock pressure and velocity decrease and the response of the pressure probes should fall further behind as the shock is attenuated. In Table IV a comparison is made between data from the smear camera and the sweep oscilloscope (Col. 5) and between the smear camera and the raster oscilloscope (Col. 6). In all but one instance the camera did record the process before the electronic systems did. However, with the exception of probes 7 and 8, placed at a distance of 72.7 and 85.3 mm from the donor, the time lag was, on the whole, less than 0.5 microseconds. The sweep oscilloscope data were slightly higher, 0.6 microseconds. To investigate further the comparative time lags in the systems an equation of the type

$$X = a + bt + ct^2 + dt^3 \qquad (2)$$

where

X = distance or gap (mm)

t = time (microseconds)

was fitted to the data by the electronic computer (IBM 704). In Table V, the first derivatives, dX/dt, obtained for experiment #5 are tabulated and compared at various time intervals. A more complete discussion of equation (2) is given in Appendix I.

For the initial 7 - 10 microseconds, the velocities calculated from the two sets of data differ by only 1%. This interval is the time required for the shock to traverse 1 3/4 inches of Lucite. For 15 - 20 microseconds (2 1/2 - 3 inches of Lucite) the velocities differ by 5 - 10%. However, the particular equation used did not hold beyond t = 20 microseconds and it may be that the difference in velocities at 3 inches or so is somewhat less than indicated.

Thus, the pressure probe may be used to interpret the shock velocity for the initial three inches of Lucite with fair accuracy and reliability (to within 10%). Beyond this, as the shock wave becomes more attenuated, the time lag increases and consequently the percentage error begins to rise very rapidly. Thus, while values at three inches may be off by only 10%, values for larger thicknesses may be in error by much more (e.g., 20% at a four inch thickness). The sensitivity of most propellants and explosives tested, however, lie below the three inch limit. Consequently the pressure probe measurements are considered fairly adequate for this work.

It should be understood that the shock wave velocities, dX/dt, reported and used to compute shock wave pressures in later sections of this report were determined graphically, not analytically. The graphically determined derivatives for both the optical and the probe data are several percent lower than the analytically determined ones of Table V. Moreover, the divergence of the probe results from the optical does not exceed 6% even at four inch thicknesses of Lucite. Indeed, the (dX/dt) vs X curve obtained from Eqn. (2) diverges at both ends of the range 0 - 20 μsec from the graphically determined (dX/dt) vs X; this is the basis for the suggestion above that the inadequacy of the data fit may be responsible for the larger percentage differences of Table V.

B. Velocity vs Distance for Lucite

The results of the experiments are plotted in Figures VII, VIII, IX and X. In Figure VII the data obtained with the

TABLE V

COMPARISON OF THE VELOCITY BETWEEN THE PRESSURE PROBE AND THE SMEAR CAMERA

Time t=microsec.	Pressure Probe dX/dt = mm/microsec.	Camera dX/dt = mm/microsec.	$\Delta = C - P_p$ mm/microsec.	% Difference
0	5.0807	5.1233	0.043	0.8
3	4.5277	4.5632	.036	0.8
5	4.2011	4.2398	.039	0.9
7	3.9083	3.9562	.048	1.2
10	3.5322	3.6058	.074	2.0
15	3.0737	3.1216	.148	4.7
20	2.8259	3.0869	.261	8.4

pressure probes are plotted. The precision of these measurements varied from a standard deviation of ± 2.3% to ± 4%. This precision includes any variation due to the probe, the position of the probe, or any variation of the Lucite or the tetryl booster. In Figure VIII a comparison is made between the data obtained with the camera and with the pressure probes. Figure IX compares the measurements made in the gap material with the curve obtained with the camera. It is quite apparent that for the distances measured the cellulose acetate and Lucite systems are comparable. Moreover for these lengths both the pressure probes and the camera give the same results for the same donor. Figure X compares the velocity of the shock fronts obtained from the slopes of the curves in Figure VIII. It is quite apparent that, as the shock was attenuated and the pressure fell, the pressure probe results began to lag behind the results obtained by the smear camera.

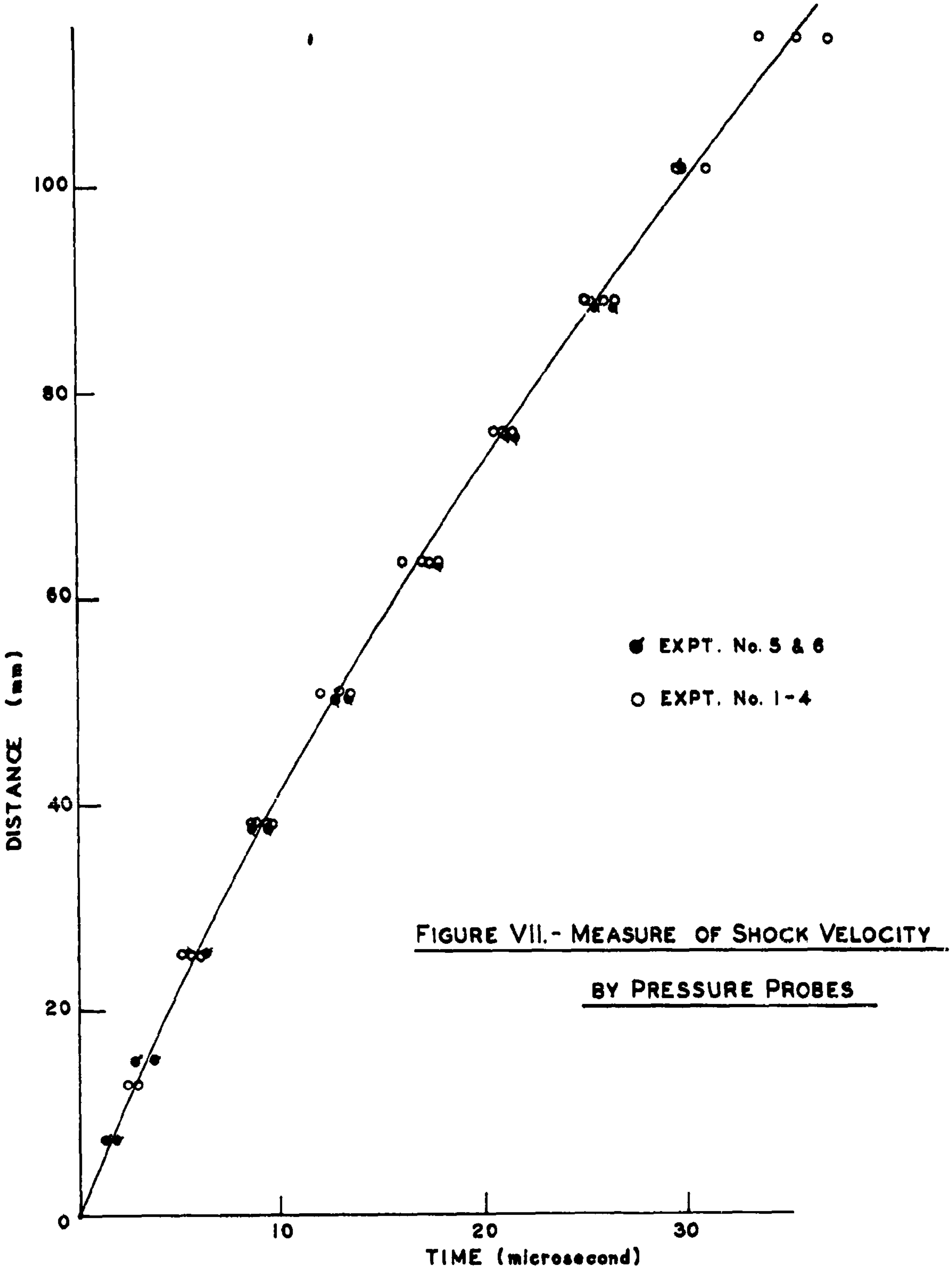

FIGURE VII.- MEASURE OF SHOCK VELOCITY BY PRESSURE PROBES

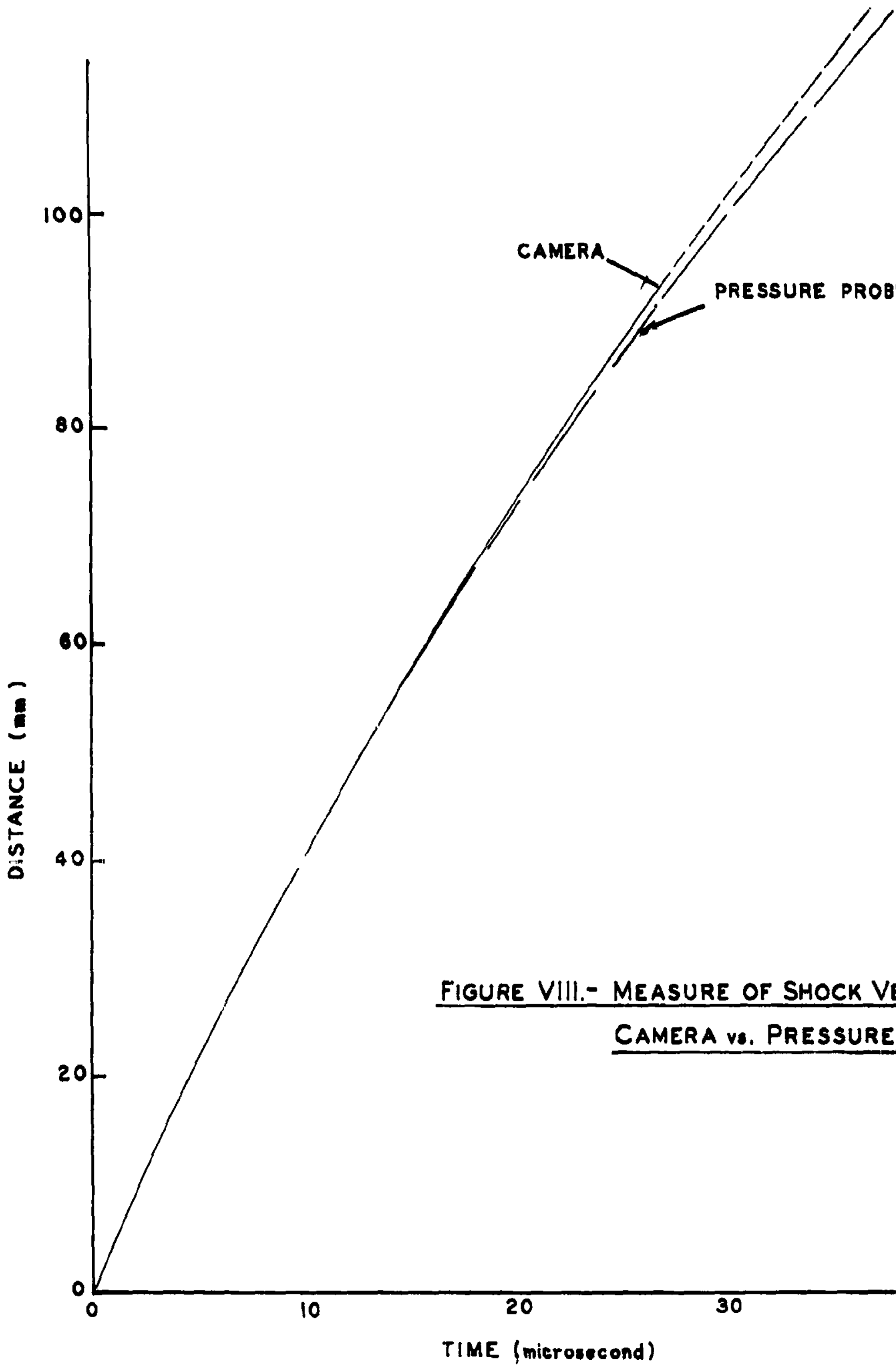

FIGURE VIII.- MEASURE OF SHOCK VELOCITY
CAMERA vs. PRESSURE PROBE

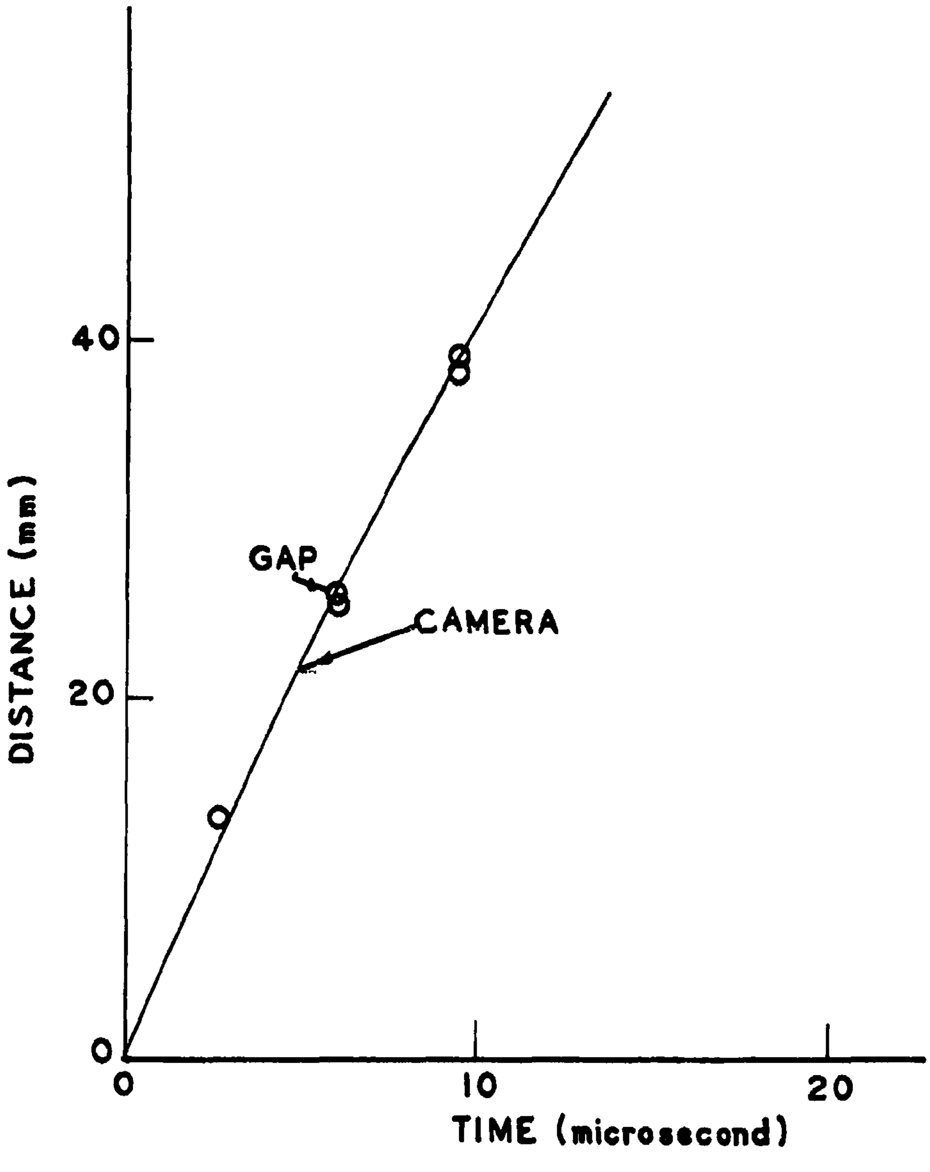

FIGURE IX - COMPARISON - GAP vs CAMERA DATA

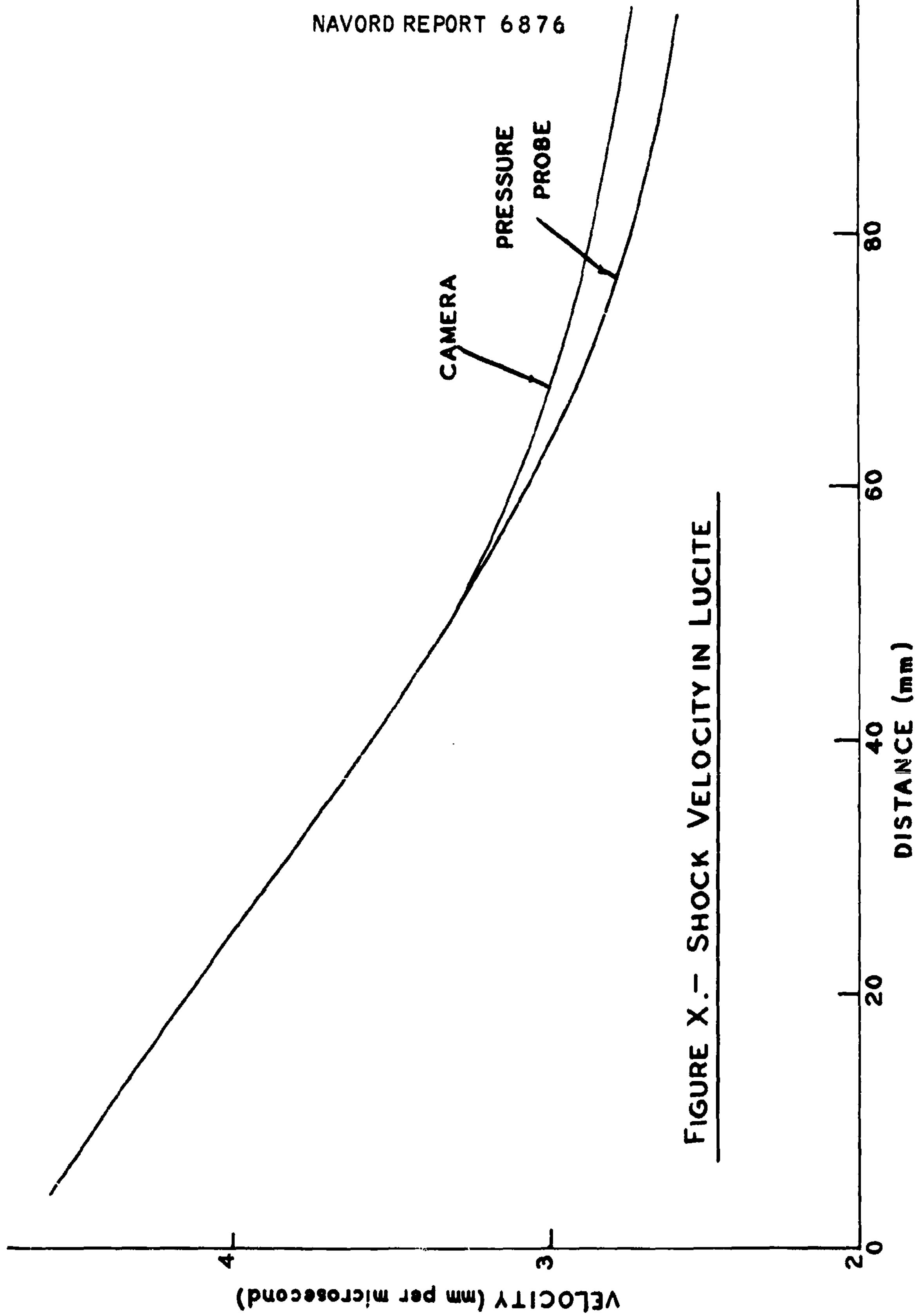

FIGURE X.- SHOCK VELOCITY IN LUCITE

In Figure XI the effects of changing the donor load from one to four tetryl pellets is shown.* The detonation pressure and velocity are defined for a given explosive system. If steady state detonation is achieved, these properties (e.g., detonation pressure, and shock velocity induced in Lucite) are not affected by the length of a charge and consequently should not change in going from a donor of one tetryl pellet to two, three, or four pellets. But the transmitted properties in the acceptor (Lucite) do, in fact, depend upon the donor loading (Figure XI). As the number of tetryl pellets is increased, the measured transmitted shock velocity increases. In some cases the transmitted velocity remains constant for a short distance in the Lucite. This was actually measured for the systems of three and four tetryl pellets.

It is known from hydrodynamic theory that the amplitude of the pressure pulse at the interface is a constant and is independent of the length of the donor. It may be assumed that the pressure profile in the explosive adjacent to the interface is fairly constant with the rarefaction following at a finite distance behind the detonation front. The distance between the shock front and the rarefaction should increase with an increase in donor length to an assymptotic value which is achieved at an infinite donor length. Actually it may be possible to attain this value by a practical donor load consisting of five or six tetryl pellets.

The wave transmitted into Lucite is modified in that it will maintain the overall shape of the incident wave, but its amplitude and duration will change. This change is in part due to the impedance mismatch between the donor and acceptor, and the geometry of the system. For short donors the approach and interaction of the rarefaction wave occur after a very short interval of time. The resulting transmitted plateau is of so short a duration that it cannot be detected by the experimental methods used in the present situation. As the donor length is increased (cf. data for 4 pellets) the distance between the shock and rarefaction fronts increases until it is large enough to allow a sufficient length of time for the transmitted plateau to be detected. A further and more comprehensive investigation of these phenomena will be made.

* The preliminary data of Table II indicate a cross-over of some of the curves after a long path of travel through the attenuator. This is attributed to the difficulty in measuring small differences and will be further investigated. Fig. XI has been confined to the area in which the measured differences are large and can be assumed real.

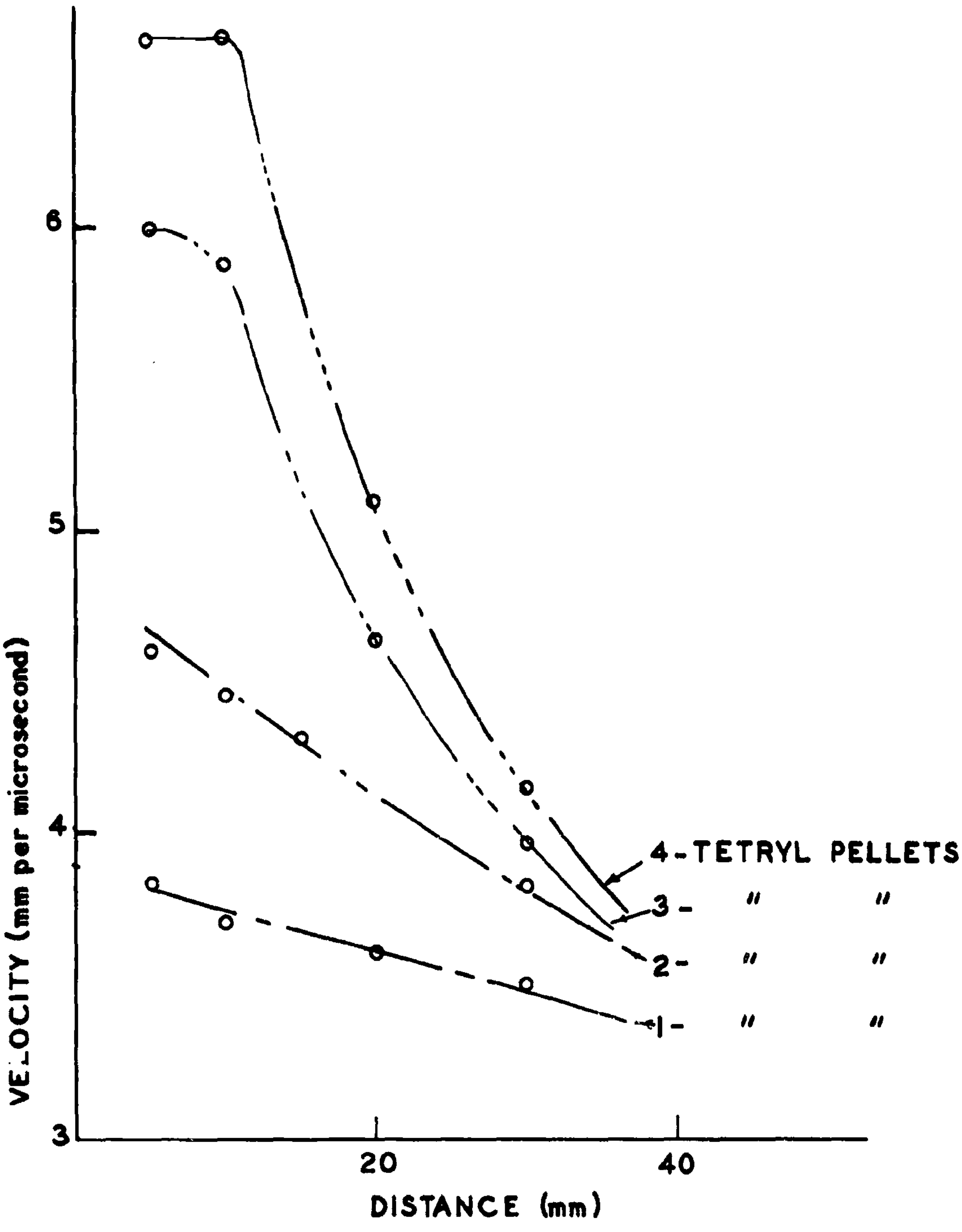

FIGURE XI.- DONOR LOAD AND SHOCK VELOCITY

C. Pressure vs Distance for Lucite

In Figure XII the particle velocity was plotted as a function of the shock velocity from the experimental data obtained on Lucite (5), Plexiglass (Ref. 6 and Appendix II) and Perspex (7). These substances are quite similar in characteristics and it is assumed that their properties in the shock region do not differ from each other. However, the lowest shock strength obtained experimentally is at the upper end of the region critical to this investigation. Most shock sensitivity results on explosives are within the gap range of 30 to 65 mm and the maximum transmitted shock velocity obtained by the two tetryl pellets is about 4.6 mm per microsecond (Figure X). The extrapolation to u = 0 is difficult since the shock pressure is obtained as a product of the particle and shock velocities.

The approximate shock pressures were obtained from the usual boundary approximations (8,9),

$$\mu_L = \mu_{H_2O} \frac{(\rho_0 U)_{H_2O} + (\rho_0 U)_L}{2(\rho_0 U)_L} \qquad (3)$$

where

μ_L = particle velocity in Lucite

μ_{H_2O} = particle velocity in H_2O

ρ_0 = density of Lucite or water

U = shock velocity in Lucite or water

in conjunction with the experimental data obtained for the shock velocity in Lucite and water, and the particle velocity for water obtained from the literature (10). The calculated particle velocity for Lucite in Eqn. (1) yields the corresponding shock pressure.

Figure XIII is a typical plot of the results (Table IV) obtained by the smear camera. The shock velocities for both Lucite and water are determined at the intersection of the respective curves which corresponds to the Lucite-water interface. Table VI contains the measured shock velocities and the corresponding particle velocities calculated by Eqn. (3). Using these points for the lower pressure region and the other data already available in the higher pressure region a straight line was drawn through all the data. This curve (Fig. XII) was extrapolated to U = 2.59 mm per microsecond at μ = 0; the

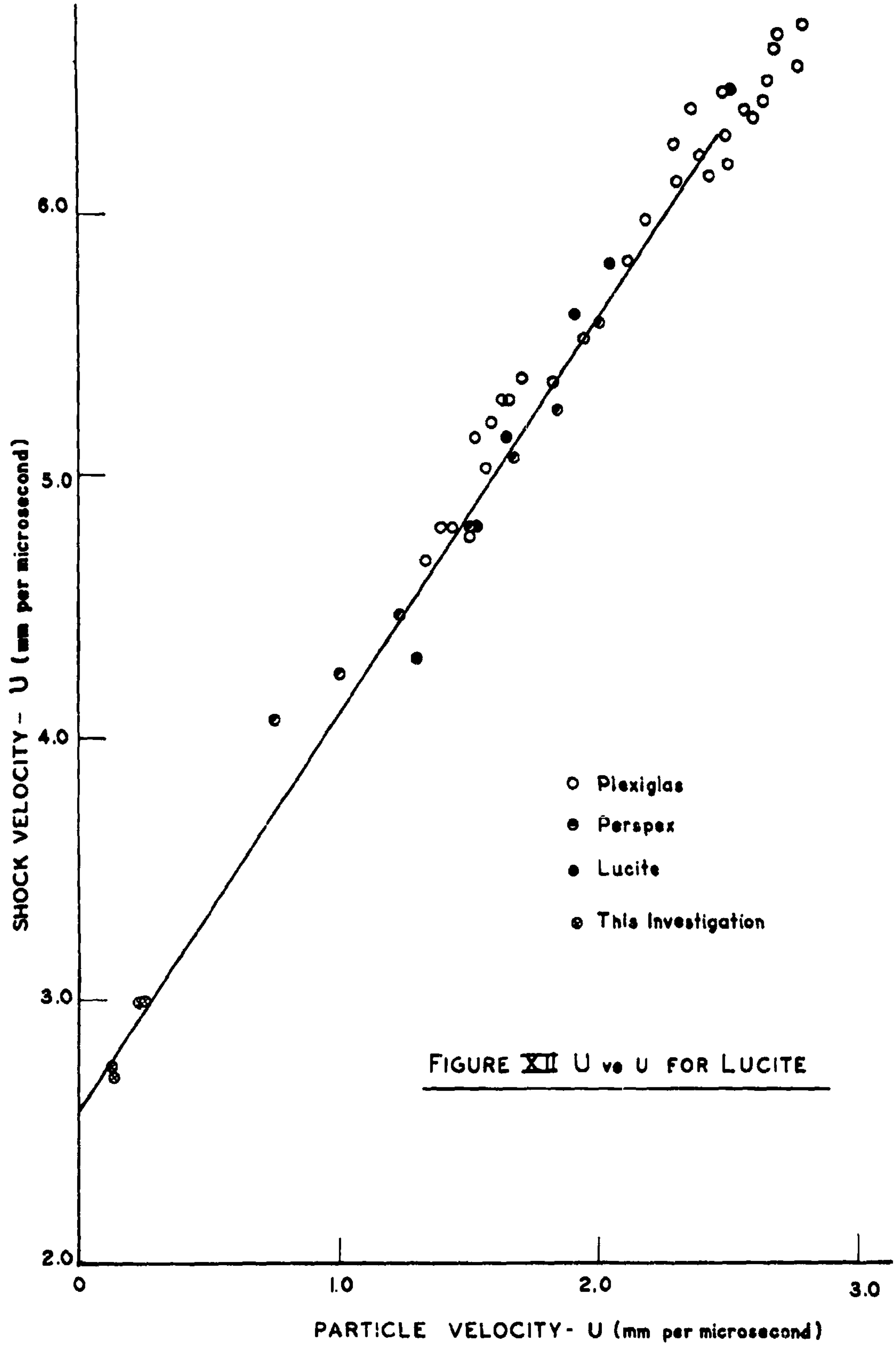

FIGURE XII U vs U FOR LUCITE

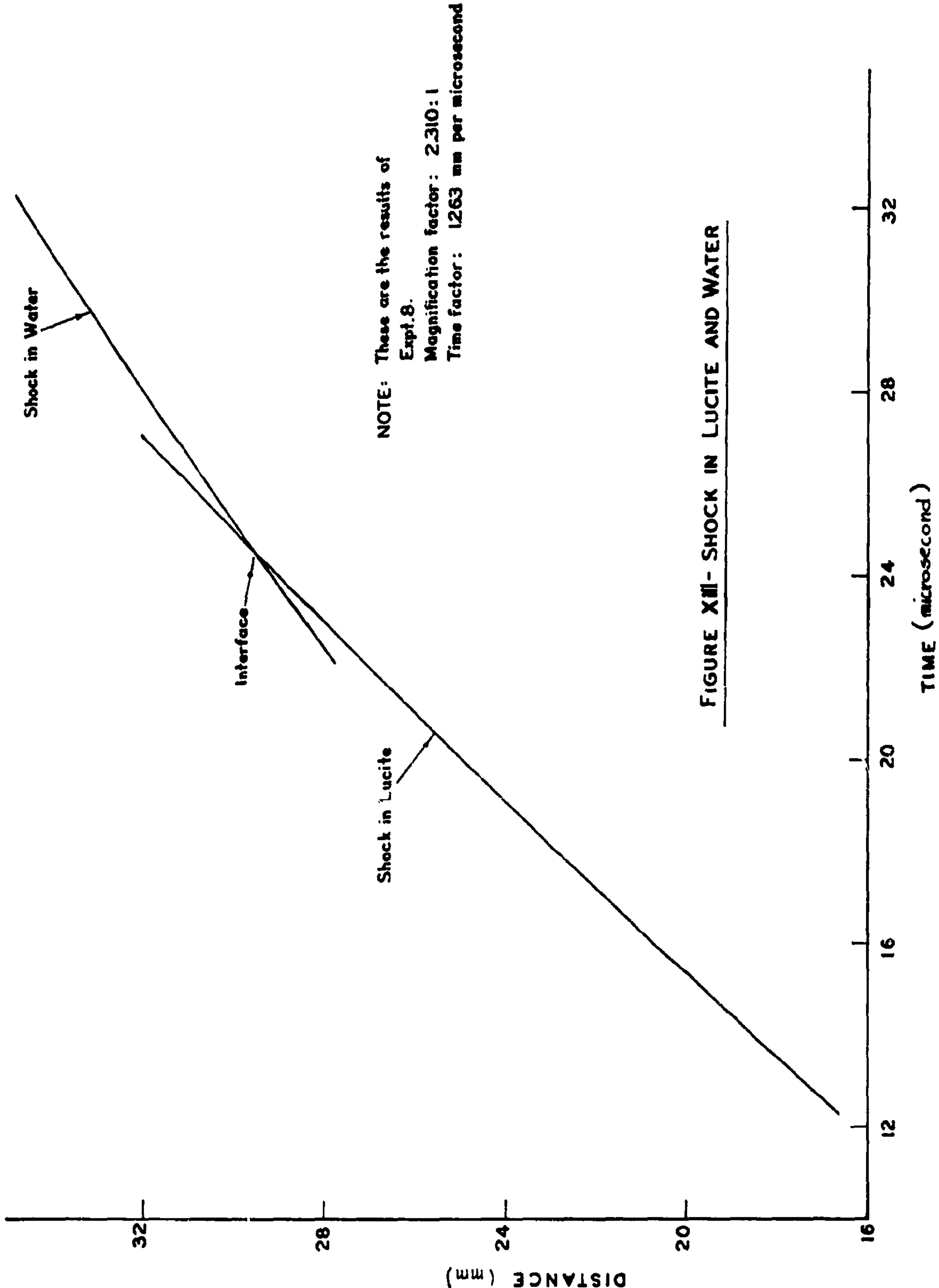

FIGURE XII- SHOCK IN LUCITE AND WATER

TABLE VI

SHOCK VELOCITY IN LUCITE AND H_2O, OPTICAL DATA

Expt. No.	Conversion Factor**	U_L mm/µsec	U_{H_2O} mm/µsec	u_{H_2O} mm/µsec	U_L(calc) mm/µsec
5	4.043	2.701	1.840	0.162	0.128
6	4.274	2.744	1.817	0.160	0.125
7	2.938	2.990	2.130	0.312	0.250
8	2.911	2.952	2.069	0.281	0.224

** The conversion factor contains both the magnification factor and time factor.

extrapolated value is approximately equal to the hydrodynamic sound velocity calculated as 2.44 mm per microsecond (Appendix III).

All the data required to develop a pressure-distance curve (P vs X) are available. From experiments 5 thru 8 a U - X curve (shock velocity vs distance, Figure X) was obtained for the specified geometry. In addition these experiments provided the data (Table VI) required to calculate and complete the U - u curve (shock velocity vs particle velocity, Figure XII). Using these two curves and Eqn. (1) ($P = \rho_0 Uu$) it is possible to calculate P - X (pressure vs distance, Table VII) and obtain the curve in Figure XIV in which the pressure appears to vary exponentially with the distance. Figure XV is a plot of log P vs X and may be approximated by the equation

$$P = 105\, e^{-0.0358X} \qquad (4)$$

These curves will allow direct interpretation of gap length in terms of shock pressure obtained at the end of the Lucite gap. While this pressure is somewhat higher than the pressure entering the acceptor because of the impedance mismatch between the donor and acceptor, it is hoped that this scale of P vs X will offer additional guidance in the sensitivity work. This is especially so since the impedance of Lucite is so near the range found for most explosives. The pressures required to initiate the explosives TNT (34.5 kbar), Composition B (19 Kbar) and tetryl (10 kbar) have been indicated in Figure XIV.

TABLE VII

CALCULATED PRESSURE AND DISTANCE DATA FOR LUCITE

Distance mm	Pressure Kbar
5	75.47
10	66.08
20	50.95
30	36.83
40	26.31
50	18.29
60	12.44
70	8.51
80	6.06
90	4.35
100	2.89

ACKNOWLEDGMENT

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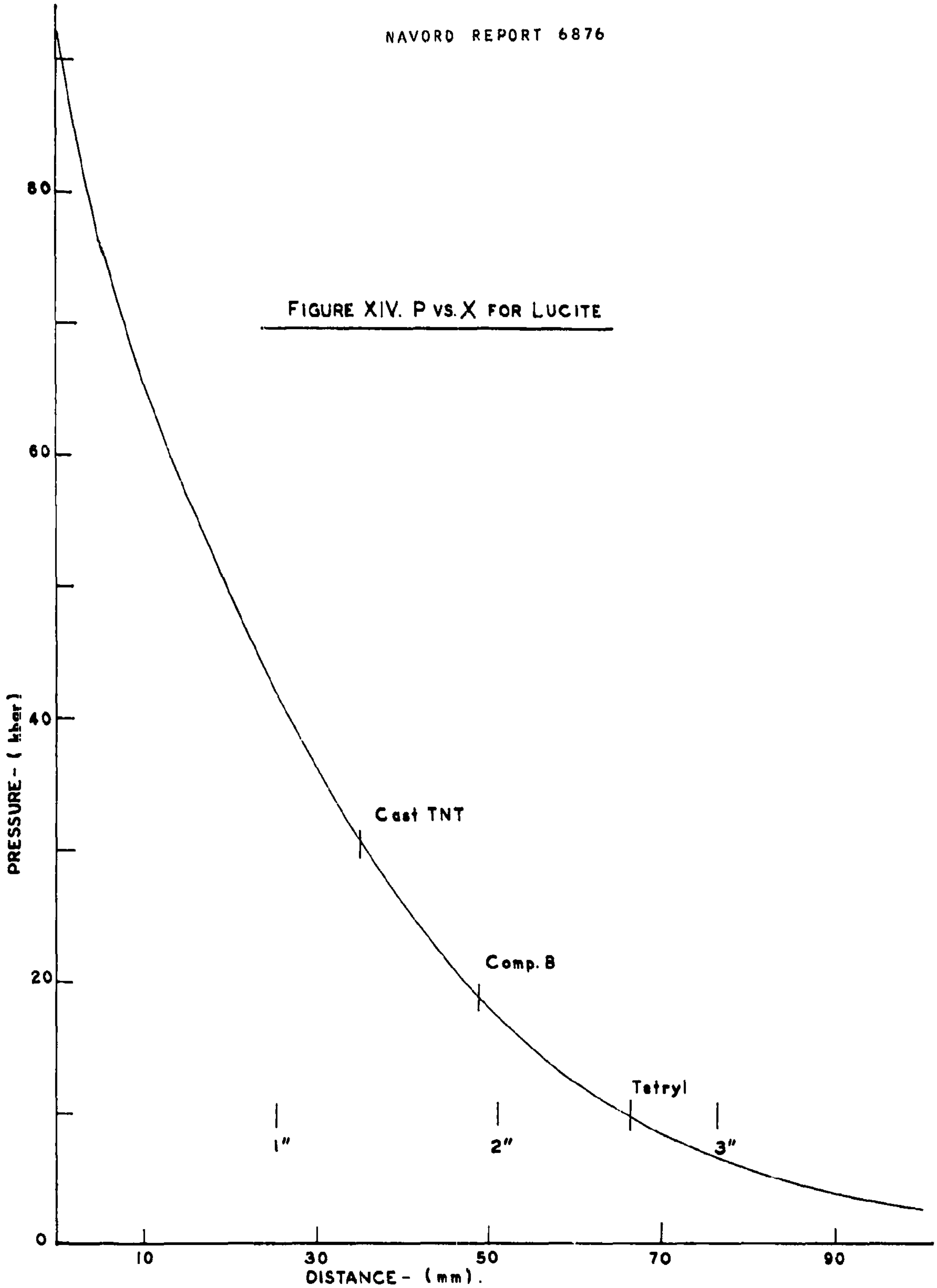
FIGURE XIV. P VS. X FOR LUCITE
PRESSURE - (kbar)
80
60
40
20
0
Cast TNT
Comp. B
Tetryl
1"
2"
3"
10
30
50
70
90
DISTANCE - (mm).

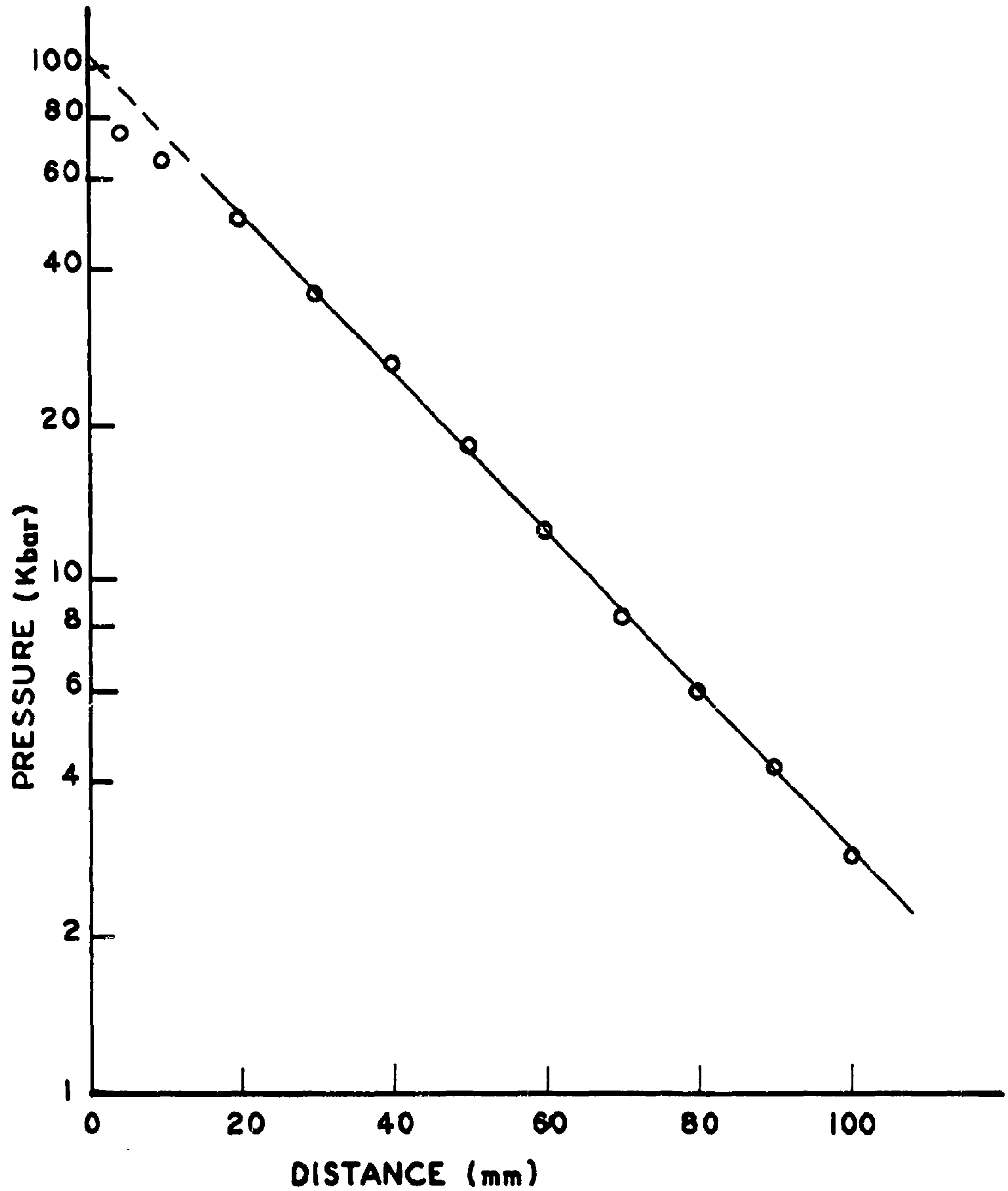

FIGURE XV - LN. PRESSURE vs. DISTANCE

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APPENDIX I

DERIVED EQUATION FOR x vs t (Distance vs Time)

The least square polynomial equations used to approximate the camera and pressure probe data (Expt. 6) were respectively:

$$X_c = -1.68002 + 5.12334t - 0.100840t^2 + 0.00166433t^3 \quad (1)$$

and

$$X_p = -2.84977 + 5.08068t - 0.0984832t^2 + 0.00140377t^3 \quad (2)$$

The following is a table in which a comparison is made between the distances calculated from the above equation (1) and the distance determined experimentally by the camera.

Time microsec.	X_c Calculated (mm)	X_c Experimental (mm)
1	3.3	4.5
5	21.6	21.7
10	41.1	41.2
20	73.8	74.1
25	89.4	88.6
30	106.2	102.6
35	125.5	115.7

APPENDIX II

EXPERIMENTAL DATA U vs u, - N. L. Coleburn

Below are the experimental data obtained from N. Coleburn determined on Plexiglass (ρ_0 = 1.180).

Shock Velocity U=m/sec.	Particle Velocity u=m/sec.	Shock Velocity U=m/sec.	Particle Velocity u=m/sec.
6730	2785	4675	1333
6692	2697	4800	1390
6628	2672	4800	1390
6574	2765	4800	1436
6522	2715	4765	1500
6431	2628	5143	1523
6369	2595	5035	1565
6300	2485	5200	1587
6195	2495	5290	1629
6143	2425	5290	1655
		5373	1707
6539	2412		
6553	2515	5360	1825
6688	2618	5530	1940
6571	2510	5690	2025
6724	2682	5830	2115
6730	2682	5980	2180
6730	2795	6130	2250
6759	2787	6270	2300
6760	2840	6400	2355
		6540	2465
6530	2449	6680	2500
6508	2456		
6468	2473		
6400	2562		
6366	2519		
6333	2381		
6297	2343		
6263	2283		
6223	2384		

APPENDIX III

CALCULATION OF THE VELOCITY OF SOUND IN LUCITE

The bulk modulus or incompressibility k is defined as the ratio of the hydrostatic pressure on a body to the fractional change in volume.

$$k = \frac{p}{-\Delta}$$

where

k = bulk modulus

p = hydrostatic pressure

Δ = negative dilatation or resultant change in volume

The negative dilatation is propagated with the velocity of

$$c = \left(\frac{k}{\rho}\right)^{1/2}$$

which is the sound velocity.

For an isotropic solid, the bulk modulus may be replaced by the Lamé elastic constants and k is obtained as

$$k = \frac{3\lambda + 2\mu}{3} \qquad (3)$$

The sound velocity derived from equations (1) and (3) is

$$c = \left(\frac{3\lambda + 2\mu}{3\rho}\right)^{1/2}$$

A more detailed development of the preceding may be obtained in reference (11).

The Lamé constants for Lucite under isothermal conditions were obtained from the 'American Institute of Physics Handbook' (12) as

$$\mu = 0.143 \times 10^{10} \text{ newtons*/m}^2$$

* newton = 10^5 dynes

$$\lambda = 0.562 \times 10^{10} \text{ newtons/m}^2$$

However, the conditions are more nearly adiabati
the velocity of sound will be somewhat higher si

$$\lambda_{ad} = \lambda_{iso} + Q$$

where Q is the correction due to heat loss and w
0.044 newtons per m^2. The velocity of sound in
calculated from the above is 2.44 mm per microse

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This publication is changed as follows:

2nd para. line 15, sentence should read as follows:

While this pressure is somewhat lower than the pressure [illegible]ing the acceptor because of the impedance mismatch between Lucite and acceptor, it is hoped that this scale of P [illegible] offer additional guidance in the sensitivity work.

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